Design and Development of an Injection Molded Prosthetic Polycentric Knee Joint for Amputee

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***Abstract*: - The purpose of the work "Developing light weight, durable and user friendly artificial limbs through Nanotechnology-based modification of conventional materials and optimizing mechanical component design for enhancing their functional performance" is to develop the efficient and economical artificial limb. The above work mainly focused to use polymers in the field of leg prosthesis. The leg prosthesis mainly consists of the four components socket, knee joint, and shank and foot ankle system. The socket holds the whole leg prosthesis to the human residual limb. The knee joint acts as the intermediate between the socket and the shank which gives the sufficient rotation which supports for walking. The foot ankle system is like our foot which gives the stability in walking throughout the entire gait cycle.**

***Index Terms*—Knee joint, FEA analysis, Stance Phase, Swing Phase, polycentric joint.**

I. INTRODUCTION

The primary goal of the project is to evaluate the design of a prosthetic knee mechanism by using finite element analysis and comparing it to the mechanical and clinical testing of the system. The Finite element model was then used to evaluate further designs as well as provide critical optimization results to the existing design. Our motivation for the analysis comes from limitations to manufacturing for our existing design as well as efficient use of resources through Computer Aided Engineering. This report begins with a description of the background and novel function of the specific knee joint. It then highlights the current manufacturing limitations of the existing design. An FEA model of the existing design will be constructed and upon confirming the results of previous mechanical and clinical testing, redesigned devices will be computationally analyzed. Compiling and comparing these FEA results will enable us to recommend a final optimized main body of the prosthetic knee joint.

The prosthetic knee design that we are working with is a single axis, self engaging lock design. Two common problems with most prosthetics is the high strain on hip muscles when the foot is placed down and instability in landing when the heel touches the ground. Unlike other prostheses that require a child to place weight on their foot before stabilizing, this prototype automatically locks when the child extends their leg. And unlike the competition, the knee is shorter so it fits proportionally with a young child's leg. Cheap and easy assembly was initially the major focus of the project. We started off by using Mold Flow software to predict the occurrence of weld lines and study the flow of plastic into the material. However, during the initial stages of the project, there were inabilities to manufacture the current plastic part at the specified thickness. This led us to concentrate on optimizing the current design to allow for the reduction in thickness. To do this, we first analyzed the current design and validated finite element analysis to the mechanical and clinical testing. The analysis was performed using ANSYS workbench academic version software package. The analysis starts with a two part assembly and moves onto a complete four part assembly. The loading conditions were specified in accordance with the International Standard Organization (ISO) test conditions for prosthetic knee joints [1]. First the load line vector was applied along specific planes and the point of contact to the top and bottom of the knee joint was recorded. This allowed us to create lever arms at specific angles to apply the load line vector to the knee assembly. The ISO conditions specified the testing of two separate conditions, one was the application of load to the foot and the other was the application of load through the heel. This simulates the swing phase and the stance phase and of gait walking respectively. The system was also analyzed from two different directions; from the top and from the bottom.

The outcome of this was a thorough understanding of the stresses that act on the current design. In addition, it was found that the heel condition loading was more severe than the toe loading, which allowed us to concentrate our analysis on the worse case condition. Two redesigned concepts were selected based on our requirements for reduced thickness. These concepts were analyzed and validated with our finite element lending to our recommendations for a final concept. Furthermore, our final element model serves as a basis for analysis of future concepts.

Before we discuss the literature review, we would like to go over some of the vocabulary used. The above knee area is termed as femoral and the below knee as the tibial region. There are two main types of knee designs; single axis and polycentric design. The single axis knee design consists of one primary axis that uses mechanical friction about a bolt, which connects the socket (thigh) to the shank (below knee). The bolt is located behind the path of the weight of the body to the floor so that it will not buckle when the user is standing straight. The polycentric design consists of a moving centre of rotation. This provides better control of the above-knee prosthesis during standing and the stance phase of walking. Another important parameter is the direction of the load lines. These lines of action depict loads applied to prosthetics, specifically used to define stability of the knee. Posterior refers to the region behind the knee and anterior refers to the region in front of the knee. Medial refers to towards or inside of the body, while lateral refers to away or outside of the body. These are important parameters in defining control axis.

A sequence of movements that mimics the human walk cycle is known as gait. The two stages of gait walking are the stance phase and the swing phase. The stance phase is where initial contact occurs at the heel and the knee is locked. When the toe is then loaded, the knee unlocks, completing the portion where the leg is in direct contact with the floor. This is followed by the swing phase where the leg is off the ground and swings back to its original configuration before it locks itself to begin the stance phase again.

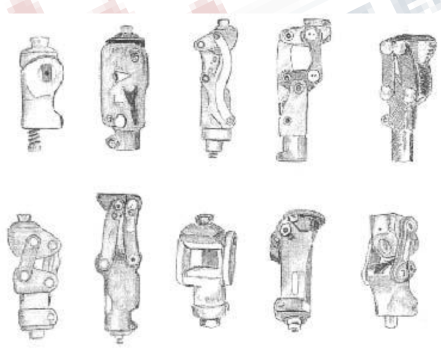

Figure 2.1 Prosthetic Designs [2]

The overall understanding of knee motion and the gait phenomenon was carried out through researching e-journals and biomedical handbooks. Two such articles pertaining directly to our area of research are discussed here. The first article is titled “Design Characteristics of Pediatric Prosthetic Knees” by Jan Andrysek, S. Naumann and W.L. Cleghorn [2]. This article focuses on assigning Design Parameters and functional requirements for the most optimal pediatric prosthetic knee. It starts of by comparing polycentric four and six bar linkages to single axis knees. The results indicate that a single-axis knee joint, with a particular axis placement and a stance phase control mechanism can satisfy most design parameters similar to polycentric knee joints. Equations Another important factor in the design of prosthetic knees is the placement of the devices axis to the weight bearing load lines. By characterizing the design parameters of stance-phase stability, toe-clearance to initiate the swing phase, maximum knee flexion angle and thigh portion length the best location for the axis is posterior. The stance phase draws the load line characteristics to design for stability. As displayed in the figure below the toe clearance is dependant on the trajectory of the lower limb during the swing phase, defined by knee and hip kinematics in relation to the ground.

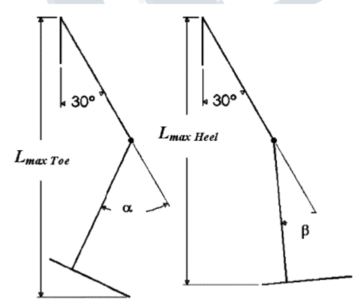

Figure 2.2 Toe & Heel Clearance [2]

Shortening and lengthening of the limb is a contributing factor for single axis knees comfort. Adequate knee flexion of 150° was defined to be the benchmark. Sitting appearance and comfort were attributed to placement of the knee axis at the posterior of the knee joint and increase in thigh length over the shank length was found to be more desirable. After analyzing six currently used knee prosthetics (comprising of four-bar, six-bar, and other polycentric and single axis knees) and employing the quality function deployment, it was concluded that a proposed single axis configuration, incorporating stance phase control could result in a highly functional, yet complex, prosthetic knee joint. This article laid the foundation to the corresponding stance phase controlled prototype design which ultimately led to the current prototype under investigation in our thesis.

The second articled is titled "Design and Quantitative Evaluation of a Stance-Phase Controlled Prosthetic Knee Joint for Children" by Jan Andrysek, S. Naumann and W.L Cleghorn [3]. This articled primarily deals with the notion that the stance phase of gait walking is the most important factor in assessing stability of the prosthetic knee and a prototype design that incorporates this is examined. The article begins by talking about the various single axis, four bar and six bar linkage mechanism available to the amputee and weighs the design parameters on (i) ensuring that the knee is fully extended during the swing phase and remains so until weight bearing to achieve stability and (ii) decrease the extent of conditions that can make the knee unstable during weight bearing. The prototype design is based on a lock-unlock mechanism that is initiated by a moment created at a control axis. The methodology for the study is described by the creation of knee instability diagrams. These diagrams depict regions of instability at the stance phase and thus allow for a better design by avoiding these regions. The maximum loads are found on toe strike during swing phase initiation and heel strike during the stance phase initiation. This allows us to define stability as a function of the line of action of these loads placed on the prosthesis, referred to as load line vectors.

Thus by evaluating the effects of these load line vectors (a) originating at the toe, (b) passing through the main knee axis and (c) passing through control knee axis, the regions of instability were assessed and avoided as much as possible while creating the new prototype. The article goes on to explain why the subjects preferred the new knee design and expressed the importance of instability zone modeling by promoting the stance phase stability in design. The relevance to our project is that our prototype design closely relates to the one described in the article. The importance of load lines and stability of the stance phase allows us to define the conditions necessary for our FEA analysis.

Another mention to our sources of literature are the ISO standard documents given to us by Jan Andrysek that consist of (a) Test Configurations, (b) Test Samples, (c) Principal Structural Tests, (d) Loading parameters, (e) Supplementary Structural tests, (f) Test submission and (g) Test Report. The load line vectors, ultimate loads and fatigue conditions detailed in the paper have been incorporated as key parameters in our FEA study.

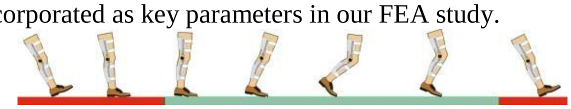

Figure 2.3 Gait walking [4]

A notable mention of our background review is the Injection Molding Handbook by Rosato. This handbook was our primary source for the first objective of our project, which was to optimize the design of the plastic components of the knee prosthetic. This included the use of Mold Flow software and understanding of injection molding techniques. The main points that related to our study are the choice of gate locations for the mold, the effects of shrinkage and the location of sink marks and weld lines. To achieve the intended design, geometric modifications will be made with the mechanical and processing behavior of plastics in mind. The use of this background information is supplemented in the Methodology and Recommendation sections.

II. DESIGN

Here we are taking an initial model with specific dimension which is being used by the automotive industries now-a-days for the purpose of transmitting torque from engine to gear part without much in loss of transmission.
Some assumptions in primary design

- The Input torque to knee joint is a constant torque without variations and the shaft rotates in constant speed.
- It has uniform annular cross section as hollow shaft has more Strength to weight ratio.
- The shaft is balanced and the Mass Center coincides with Geometric center of shaft.
- It obeys Hook's Law.
- No fluid interaction like no lubrication environment is considered.
- No vertical forces, hence no bending moments.

The transmission shaft is checked for its Torque carrying capacity, torsional deflection, Torsional Buckling capacity & Natural frequency. If Torque carrying capacity, T of the shaft which is nothing but Load factor x Input torque (Assume Load factor=1) &Ss is shear strength, t is the thickness of shaft,(do-di)/2

$$T = S_s \frac{\pi(d_0^4-d_i^4)}{16td_0} \quad (1)$$

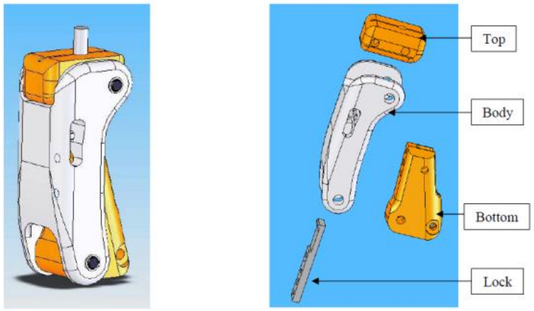

Fig 2. Existing design

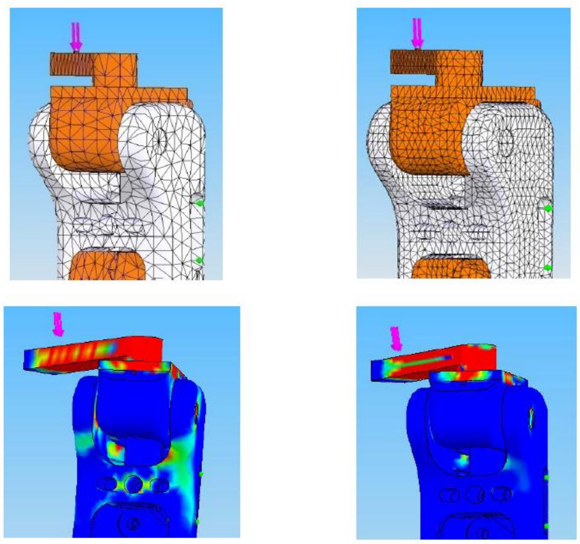

Fig 2 A. Stress Analysis for the Existing knee joint

A. Modified cad model design

An aspiration of this work is weight optimization to give better performance. After some thoughts on finalizing knee joint by using Adams software for the link optimization,

$$d = \left(\frac{16n}{\pi}\left\{\frac{1}{S_e}\left[4(K_f M_a)^2 + 3(K_{fs} T_a)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(K_f M_m)^2 + 3(K_{fs} T_m)^2\right]^{1/2}\right\}\right)^{1/3} \quad (2)$$

As per standard of ASME method of minimum diameter, B106.1M-1985 is

$$d = \sqrt[3]{\frac{32 Safety\ Factor}{\pi}\sqrt{\left(K_f \frac{M_a}{S_f}\right)^2 + \frac{3}{4}\left(\frac{T_m}{S_y}\right)^2}} \quad (3)$$

Where,

M_a, M_m, T_a, and T_m are alternating and mean bending moment as well as torques. S_f or S_e, S_y, S_{ut} are shaft material`s endurance, yield and ultimate strengths. Dimensionally.

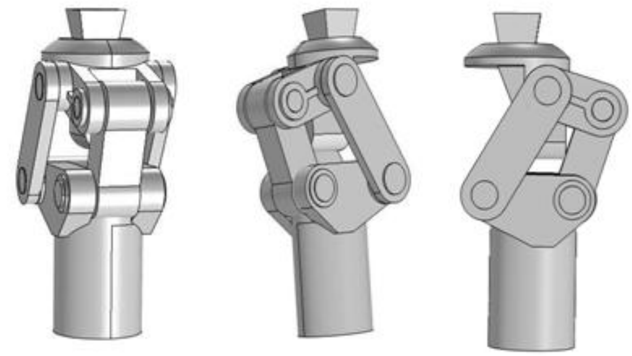

Fig 2. Present design

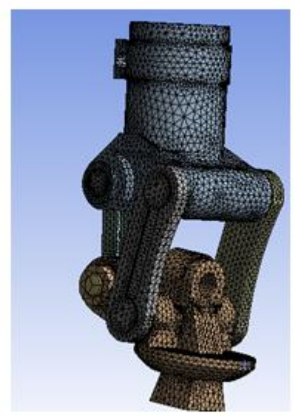

Fig 3. Meshing

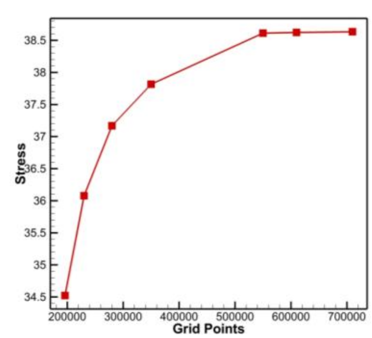

Fig 4. Grid Independence Test

In first step, the cad model of the polycentric knee joint in PRO-E cad software with the help of four bar links satisfying double-rocker mechanism was developed. The link lengths used are 40, 36, 22.48 and 43.38. The link length is optimized under to get the maximum flexion angle. The design was made help of the mathematical formulations (3).

The grid independence study is based on the six different grid systems. The graph shows that total nodes of 5 lacks has optimal value. The FEA results on the current design.

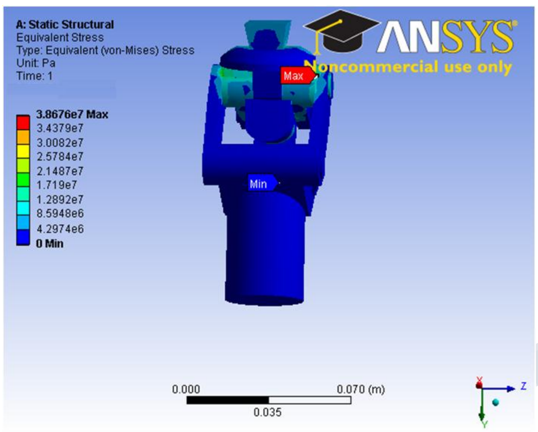

Fig 4 Von-Mises stress Analysis of stance phase

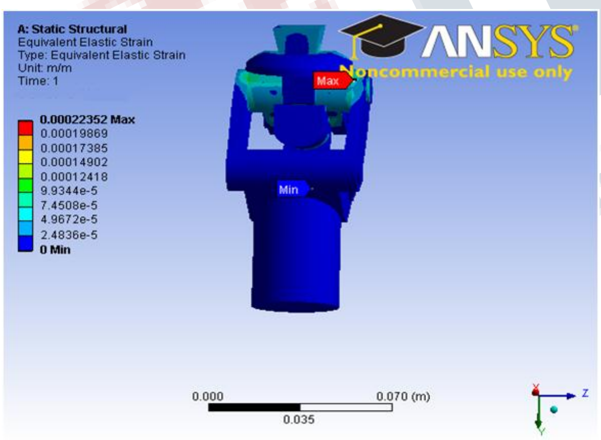

Fig 4 Strain Analysis

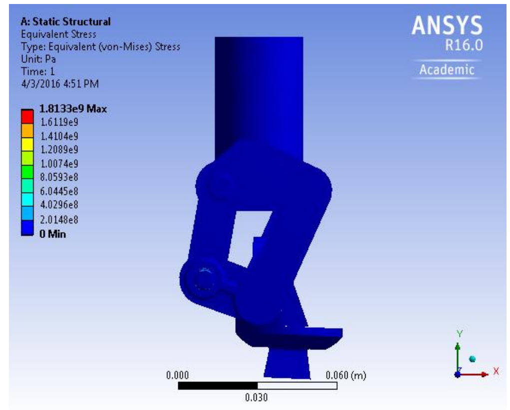

Fig 5 Von-Mises stress Analysis of stance phase in side direction

The cad model of four bar polycentric knee joint is shown in fig (2) .The FEA analysis of the above cad model is shown in the fig 3 and fig4/ below. The static structural analysis of the above cad design i.e. four bar polycentric knee joint with the material of structural steel shows the maximum stress develop is around 110 MPa under stance phase condition for the person's weight of 70 kg. For the structural steel the Factor of Safety is 2.27. The knee joint made of structural steel is not preferred because the weight of the knee joint will be high. For the same design, if the aluminum alloys used means the maximum stress developed is around 50 MPa. The Factor of Safety getting is 2-7 i.e for different al alloys. The above design is giving good results for the al alloys but the difficult is that the cost of al alloys where so high. The polymers are giving the some nearer results, in polypropylene with CNT 0.05% the maximum stress developed is around 30 MPa .By comparing the results under different polymer materials ,the proposed and optimized redesign with suitable material will be made.

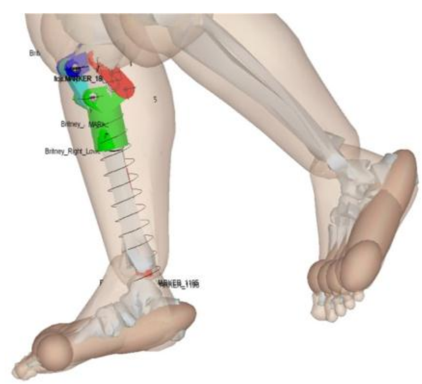

Fig 5 Life Mod Testing

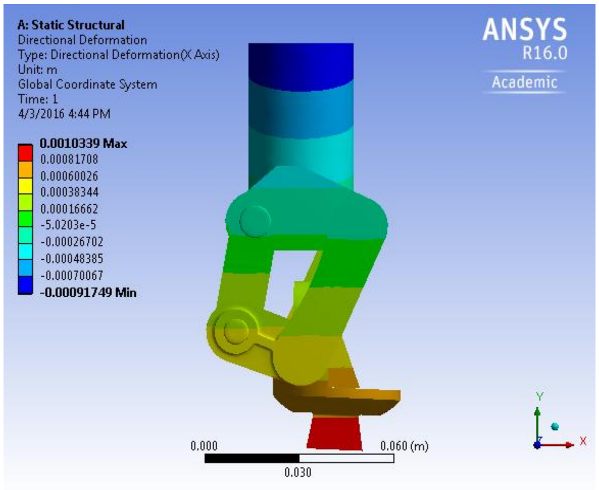

Fig 5A Directional Deformation of stance phase in side direction

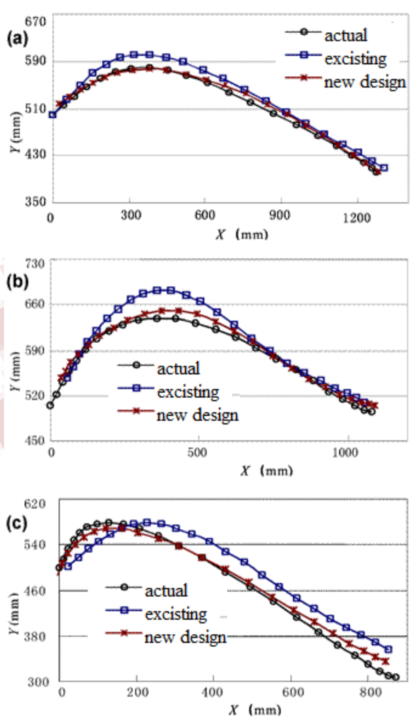

Fig 6 Gait cycle pattern comparison with the actual and current knee joint

III. CONCLUSION

In order for the prosthetic leg to be manufactured as cheaply as possible an efficient mold must be designed for mass production. This brings us back to our previous design goal of using Mold Flow analysis to predict the gate locations, number of gates, mold cycle times and temperatures to:

- Minimize warping, deformation due to shrinkage
- Minimize internal stresses
- Eliminate weld lines in critical locations
- Eliminate voids increase dimensional stability [9]

Since this plastic part is used in a structural application, the elimination of defects in high stress regions is critical. We can predict the occurrence of weld lines at the eyelets since flow would meet as it rounded the hole [10]. Thus it has been suggested that the holes be filled only partially so as to minimize the weld lines at this vital load bearing location. These holes will then require post process machining at an added cost, but this tradeoff is necessary to maintain structural integrity of the area

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